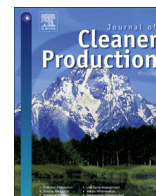




Since January 2020 Elsevier has created a COVID-19 resource centre with free information in English and Mandarin on the novel coronavirus COVID-19. The COVID-19 resource centre is hosted on Elsevier Connect, the company's public news and information website.

Elsevier hereby grants permission to make all its COVID-19-related research that is available on the COVID-19 resource centre - including this research content - immediately available in PubMed Central and other publicly funded repositories, such as the WHO COVID database with rights for unrestricted research re-use and analyses in any form or by any means with acknowledgement of the original source. These permissions are granted for free by Elsevier for as long as the COVID-19 resource centre remains active.



Environmental challenges from the increasing medical waste since SARS outbreak

Yujun Wei ^{a, b, 1}, Meng Cui ^{c, d, *, 1}, Zhonghua Ye ^e, Qingjun Guo ^{c, f}

^a Institute of Geographic Sciences and Natural Resources Research, Chinese Academy of Sciences, Beijing, 100101, China

^b Qianhai Institute for Innovative Research, Shenzhen, 518052, China

^c Center for Environmental Remediation, Institute of Geographic Sciences and Natural Resources Research, Chinese Academy of Sciences, Beijing, 100101, China

^d University of Chinese Academy of Sciences, Beijing, 100049, China

^e School of Public Policy and Management, University of Chinese Academy of Sciences, Beijing, 100049, China

^f College of Resources and Environment, University of Chinese Academy of Sciences, Beijing, 100190, China

ARTICLE INFO

Article history:

Received 18 April 2020

Received in revised form

13 November 2020

Accepted 20 November 2020

Available online 24 November 2020

Handling editor: Prof. Jiri Jaromir Klemes

Keywords:

Medical waste

Medical pollutant

Medical services

Health care institutions

Trend forecasting

ABSTRACT

Medical waste is a special class of hazardous pollutants. Improper treatment would cause secondary environmental pollution, especially when responding to public health emergencies. However, there are relatively few researches on the generation of medical waste, and there is a lack of basic understanding of its spatial-temporal heterogeneity. The outbreak of SARS in 2002 is a turning point in China's medical system reform. We estimated the production of medical waste and pollutants on a provincial scale in China from 2002 to 2018, using the data of medical statistics. Moreover, we forecasted the trend of medical waste in China until 2030, using a combination of environmental pressure model (STIRPAT) and time series model (ARIMA). We found that with the development of China's medical system and economy (such as the increase in personal income and popularization of universal health care), the number of seeking medical treatment rapidly increase led to explosive growth in medical waste (~240%) and pollutants (~260%), and large hospitals are the major sources. By 2030, the production of medical waste would still increase by more than 50% compared with 2018 even there is no the pandemic due to the huge population. The production of medical waste in the eastern region was higher than that in the west under the influence of higher population and GDP, while the per capita medical waste was only affected by household consumption level which had no regional characteristic. Additionally, Hg loads from medical waste are more than twice as high as that from discharged wastewater in some regions, which are facing great control pressures. In the future, when planning for medical waste disposal, policymakers shall increase the disposal facilities based on population and promote mobile treatment equipment to improve efficiency, increase the number of beds in medical institutions rather than building more hospitals, and strengthen basic research on the environmental impact.

© 2020 Elsevier Ltd. All rights reserved.

1. Introduction

Since the outbreak of the Novel Coronavirus (COVID-19), a large amount of medical waste has generated in the fight against public health emergencies (Silva et al., 2020). The management and environmental risks of medical waste have attracted widespread

public attention again (You et al., 2020). Medical waste is a special pollutant with characteristics of infectious, polluting and toxic generated by health care institutions in the course of medical diagnosis and treatment (Lee et al., 1991). Compared with general solid waste, medical waste has a higher risk of environmental pollution, which usually carries a large number of viruses, germs, chemical pollutants and even radioactive materials (Chaerul et al., 2008).

In recent decades, the production of medical waste has grown rapidly, due to the continuous advancement of medical technology and remarkable increase of medical treatment. Illegal dumping and inappropriate disposal of medical waste may cause secondary harm

* Corresponding author. Center for Environmental Remediation, Institute of Geographic Sciences and Natural Resources Research, Chinese Academy of Sciences, Beijing, 100101, China.

E-mail address: cuim.17b@igsnr.ac.cn (M. Cui).

¹ Contributing to this article equally.

to human health and pollutant the environment. The open-air storage of medical waste can release a mass of harmful gases such as methane and sulfide, which seriously pollutes the atmosphere (Hossain et al., 2011). Moreover, Polychlorinated biphenyls and dioxins, which are carcinogens, released during incineration (Windfeld and Brooks, 2015). Pathogens, heavy metal and organic pollutants carried by medical waste that has unqualified for disposal can cause severe pollution to surface water and groundwater through runoff and infiltration (Butt et al., 2008). Heavy metals in the landfill leachate enter the soil under the effect of leaching and washing by rainfall, which results in changes in soil properties and accumulation of heavy metals, and ultimately affect the survival of animals and plants (Mavakala et al., 2016).

At present, studies on the medical wastes generation and management mostly focused on the developing countries and limited areas (Caniato et al., 2015), such as Iran (Taghipour and Mosafari, 2009), Egypt (Abd El-Salam, 2010), Thailand, Pakistan, Mongolia (Ali and Kuroiwa, 2009), and China (Zhang et al., 2013). Due to the population explosion and inadequate medical waste management, developing countries are facing greater health risks and environmental pressure (Windfeld and Brooks, 2015). Compared with other developing countries in Asia and Africa, the overall level of medical treatment and waste disposal is relatively good in China. However, large amount of medical waste brought by Severe Acute Respiratory Syndrome (SARS) from 2002 to 2003 still posed severe challenges to China's medical waste disposal system. Since then, China has adopted a series of countermeasures to deal with medical waste (Yang et al., 2009), such as promulgated laws and regulations, *Regulations for Medical Waste Management*, *Classification Catalogue of Healthcare Waste* and *Medical Measures for the Administration of Medical Wastes in Medical Institutions* in 2003. In addition, China has built a large number of medical waste disposal facilities. The number of nationally planned medical waste disposal facility projects in 2012 doubled compared to that in 2004 (Chen et al., 2013). Fiscal expenditure from the Chinese government to promote health care increased from 0.9 billion CNY (about 13 billion USD, 0.7% of GDP) in 2002 to 1.6 trillion CNY (about 230 billion USD, 1.8% of GDP) in 2018 (Fig. S1). However, the development of the economic and medical systems in various regions of China is extremely uneven, resulting in different capabilities in treating and managing medical waste. For instance, Gansu Province in the west disposed of 6767 tons in 2013 (Sun et al., 2015), while Hubei Province that is one of the regions with the largest amount of medical waste in China, disposed of about 27,041 tons in 2014 (Zhu et al., 2016). This imbalance would bring potential danger to cope with medical waste from public health emergencies.

Although many scholars have carried out a lot of research on the treatment and management of medical waste to reduce the harm of medical waste, there are still few studies on the national medical waste production, spatial-temporal heterogeneity and influencing factors. To make up for this insufficiency, and to deal with the threat of medical waste brought by future public health emergencies, this study used public medical statistics (i) to investigate discharge of medical waste and related pollutants in China since SARS outbreak; (ii) to visualize their temporal and spatial distribution; (iii) to analyze the drivers of changes in medical waste; (iv) quantify the impact of socioeconomic factors based on STIRPAT model, and (v) to forecast future change of medical waste without pandemic influence.

2. Materials and methods

2.1. Study area and selected parameters

The study area includes 31 provincial administrative regions in mainland China, excluding Hong Kong, Macau and Taiwan because

of unavailable data. According to the statistical practice of the National Bureau of Statistics of China, mainland China is divided into six regions (Fig. S2). North China (NC) includes Beijing, Tianjin, Hebei, Shanxi, and Neimenggu (Inner Mongolia); Northeast China (NEC) includes Liaoning, Jilin, and Heilongjiang; East China (EC) includes Shanghai, Jiangsu, Zhejiang, Anhui, Fujian, Jiangxi, Shandong, and Taiwan; Central South China (CSC) includes Henan, Hubei, Hunan, Guangdong, Guangxi, Hainan, Hong Kong, and Macao; Southwest China (SWC) includes Sichuan, Guizhou, Yunnan, Chongqing, and Xizang; Northwest China (NWC) includes Shaanxi, Gansu, Qinghai, Ningxia, and Xinjiang (Tibet).

The medical institutions and the visits used in this study were divided into nine categories and four categories, respectively. The medical institutions mainly include hospitals, primary health care institutions, specialized public health institutions, and other medical institutions. Hospitals consist of general hospitals, hospitals specialized in traditional Chinese medicine, hospitals of integrated traditional Chinese medicine with western medicine, hospitals for ethnic minorities, specialized hospitals and nursing hospitals. Other medical institutions include nursing homes, clinical testing centers, medical research institutions, medical education institutions, medical examination centers and other health institutions. The total number of visits includes outpatient visits, emergency visits, individual health checks, and health consultations, excludes inspections, treatments and health management services in accordance with medical orders.

Medical waste and pollutants calculated in this paper mainly derived from the output of the above medical institutions, excluding laboratory and animal epidemic prevention. The First National Pollution Source Census recommended that using the number of beds in medical institutions and pollutants producing coefficients to estimate the production of medical waste and medical pollutants (CPSC, 2010). On this basis, we added two parameters, rates of bed utilization and the number of visits, to obtain results that are more reasonable. More details are shown in the Supplementary (Tables S4–S5).

2.2. Estimation methods

Our estimated source of medical waste consists of inpatients and visits. The formula for calculating medical waste is as follows:

$$A = \sum_{i=1}^{31} \left(\sum_{j=1}^9 (B_{i,j} \times R_{i,j} \times F_{i,j} \times 365) \right) + \sum_{i=1}^{31} \left(\sum_{m=1}^4 \left(\frac{D_{i,m}}{25} \times Q \right) \right) \quad (1)$$

where, A is the total amount of medical waste production (kg/yr) in China, i is the province, j and m represent the type of medical institutions, B is the number of beds in the medical institutions, R is the utilization rate of hospital beds, and F is medical waste producing coefficients ($\text{kg bed}^{-1} \text{ day}^{-1}$). D represents the times of annual visits, and Q is the average mass of medical waste per 25 person-times (that is 1 kg) from visits. Wang et al. (2013) and Yang (2018) estimate waste production from visits based on an average of 1 kg of medical waste generated every 20 to 30 person-times, therefore, this study used the median value 25. The calculation of the number of visits consists of the total number of visits in all hospitals and the number of visits in primary medical institutions. Visits data of primary medical institutions mainly came from community health service centers, community health service stations and township health centers.

Medical pollutants calculated in this study mainly include chemical oxygen demand (COD), five-day biochemical oxygen demand (BOD₅), total nitrogen (TN), ammonia nitrogen (NH₄⁺-N), total

phosphorus (TP), and mercury (Hg). Our calculated pollutants only include the source of the hospitalization because of lack of visits data. The calculation formula is as follows:

$$P = \sum_{i=1}^{31} \left(\sum_{j=1}^9 (B_{i,j} \times R_{i,j} \times f_{i,j} \times 365) \right) \quad (2)$$

where, P represents the total amount of a certain pollutant (kg/yr) in China, and f represents the pollutants producing coefficients (kg bed⁻¹ day⁻¹). The other parameters have the same meaning as equation (1).

2.3. Driving factors and trend analysis

This study utilized the STIRPAT model to analyze the impact of medical and socio-economic factors on the amount of medical waste production. IPAT is a traditional model that quantifies the impact of human activities on the environment, which can only analyze one factor at a time and assume other factors remain unchanged (Ehrlich and Holdren, 1971; Shi, 2003). The STIRPAT model is an improved environmental stress analysis method based on the IPAT model, which allows multi-factors and nonlinear analysis of anthropogenic impact on the environment (York et al., 2003a, 2003b). This model has been widely used in carbon emissions (Yang et al., 2018), water footprint (Zhao et al., 2014), energy consumption (Ji and Chen, 2017), solid waste (Arbulu et al., 2017).

Its standard form is:

$$I = aP^bA^cT^de \quad (3)$$

where, I , P , A , and T represent environmental impact, population, affluence, and technology level, respectively. a is the model coefficient, b , c , and d are the indices to be estimated, and e is the error term. Taking the logarithm of both sides of equation (3) to obtain the following formula:

$$\ln I = \ln a + b \ln P + c \ln A + d \ln T + \ln e \quad (4)$$

To understand how medical services and socio-economic development drive the changes in medical waste production, we analyzed a series of representative factors, including the number of hospitalizations and visits, the number of medical institutions and beds, population, government health expenditure and household consumption level. We divided P in the original formula into the population, inpatient and visits. A is divided into government health expenditure and household consumption. Moreover, the number of institutions and beds indicate T . We extended equation (4) to build an alternative formula as follows:

$$\ln W = \ln a + \beta_1 \ln P + \beta_2 \ln In + \beta_3 \ln V + \beta_4 \ln G + \beta_5 \ln H + \beta_6 \ln M + \beta_7 \ln B + \ln e \quad (5)$$

where, W is the total amount of medical waste production in China, P is the total population, In is the number of inpatients, V is the number of visits, G is government health expenditure, H is the household consumption level, M is the number of medical institutions, and B is the number of beds in all institutions. β is the elastic coefficient. Because socio-economic data usually has collinearity, we used ridge regression to solve it to avoid the effects of multiple collinearities between factors. Before solving the equation, each parameter needs to be dimensionless standardized.

Autoregressive Integrated Moving Average model (ARIMA) is a time series predictive analysis method (McKenzie, 1984). The

model structure includes three parts, autoregressive model (AR model), the difference (I) and the moving average model (MA model). First checking the variance of the data to identify the stationarity of the sequence. Then smoothing the non-stationary sequence and establishing the corresponding model in terms of the partial correlation function of the time series model. After determining the model, the statistical significance of the parameters was tested, and the residual sequence was diagnosed as white noise. Finally, the model, which had passed the test, would be conducted for predictive analysis.

2.4. Data availability and uncertainty analysis

The medical and socio-economic data in this paper derived from the National Bureau of Statistics of China and official data, including China Statistical Yearbook (NBSC, 2001–2019a), China Rural Statistical Yearbook (NBSC, 2001–2019b), and China Health Statistical Yearbook (NHCPRC, 2001–2019). Pollutants producing coefficients derived from the First National Pollution Source Census (CPSC, 2010).

In this study, the Crystal Ball software specially used for Monte Carlo simulation was used for uncertainty analysis of medical waste generation. We first traverse all possible fitting distributions on the data through the software's automatic fitting function, and select the best fit from them. The results of each year are all lognormal distributions. This selection process can be completed automatically by software, avoiding human subjective influence. The values of lognormal distribution, such as the minimum, arithmetic mean and standard deviation, we adopted the recommended values produced by the software. Then we randomly sampled the parameters and performed 10,000 simulation to obtain the average of the calculated results and a 95% confidence interval.

3. Results and discussion

3.1. Changes in Chinese medical services since SARS

Since the outbreak of SARS, the Chinese government has implemented a series of reform measures to respond to the demands of the population for medical treatment and improve the ability of the medical system to respond to public health emergencies (Li and Gao, 2017; Yao et al., 2013). For example, China extended the coverage of basic medical insurance to reduce the burden of individual payments, standardized the management of medical institutions, and improved the medical security system and disposal capacity of medical waste. To understand the influence of these changes on medical waste and pollutants, we have examined changes in medical services since 2002 (Fig. 1). Our results showed the improvement of medical services conditions had significantly promoted medical activities. For example, since 2002, the number of visits and inpatients had a significant positive correlation with changes in population and coverage of basic medical insurance, and positive correlation with the number of medical institutions and beds ($p < 0.05$) (Fig. 2, Table S1).

The largest proportion of various medical institutions is the primary health care institution, which usually undertakes lots of basic illness diagnosis and treatment. The times of annual visits to township health centers are between 700 million and 1.1 billion in recent years (NBSC, 2001–2019a). Affected by the Regulations for the Management of Rural Doctors and other relevant regulations, many rural health clinics with irregular management were canceled in 2003, such as privately run clinics (reduction of about 100,000). This change led to the total number of medical institutions dropped by nearly 200,000 (Fig. 1A). However, through the training and qualification of primary medical staff and

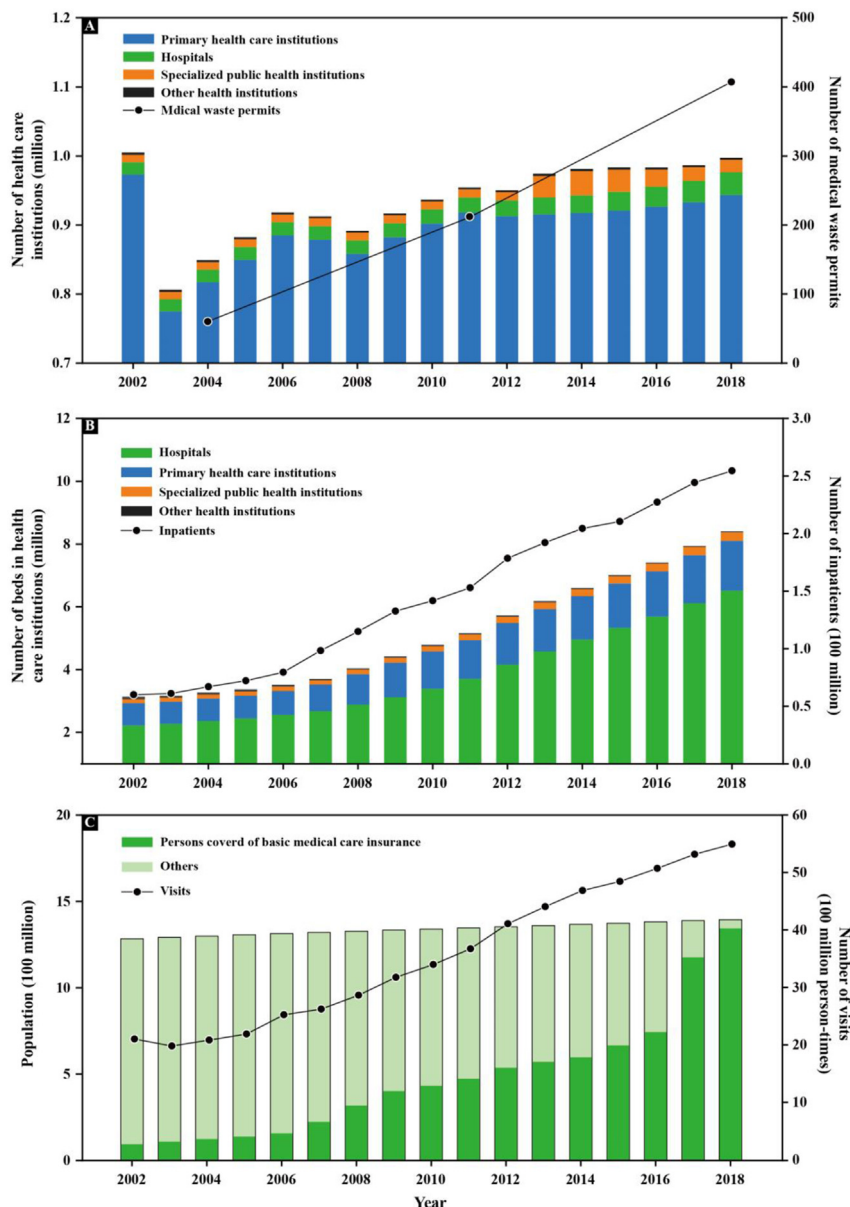


Fig. 1. Changes in medical services in China. (A) Composition of medical institutions and number of medical waste permits approved by the government. (B) Number of beds in medical institutions and inpatients. (C) Population covered by health insurance and the number of visits. Visits statistics were derived from hospitals, community and township. The original data collected came from [NBSC \(2001–2019a; 2001–2019b\)](#).

normalizing the construction of village clinics, the number of primary health care institutions recovered to a higher level after less than three years. Compared with 2003, the total number of medical institutions in 2018 increased by about 200,000, of which hospitals nearly doubled (from 18,000 to 33,000), and specialized public health institutions increased by nearly 80% (from 11,000 to 18,000).

The increase in medical institutions means disposing of more complex medical waste and pollutants. Different from general diagnosis and treatment, hospitalization continually generates a mass of medical wastes, and the actual number of available beds has a potential impact on waste and pollutants production. The number of beds in hospitals accounts for 72%–78% of the total in all medical institutions in China since 2002. The number of hospitals increased by 85%, and beds increased by 193% from 2002 to 2018 (Fig. 1B). The average ratio of beds to hospitals increased from 125 to 198. The increase in beds has enabled more patients to be

effectively treated, and hospitalizations increased from 60 million in 2002 to 250 million in 2018 (Fig. 1B). The popularity of basic medical insurance (7% of the population in 2002 increased to 96% in 2018) (Fig. 1C) has also led to more opportunities for treatment (Fig. 2), especially in rural (Chen et al., 2018; Dai et al., 2016), and the visits reached 5.5 billion in 2018 (increased nearly 160% compared to 2002).

To ensure timely disposing of the growing medical waste, China has built a large number of centralized medical waste facilities (Yang et al., 2009). The number of medical waste permits approved in 2018 increased by nearly seven times compared with 2004 (from 60 to over 400) (Fig. 1A). Annual disposal capacity of 149 centralized disposal facilities nationwide was approximately 438,000 tons in 2004 (Sun et al., 2007), however, the actual disposal quantity in 2018 reached 980,000 tons (MEE, 2019). During the pandemic of COVID-19 in China, the daily quantity of medical waste disposal

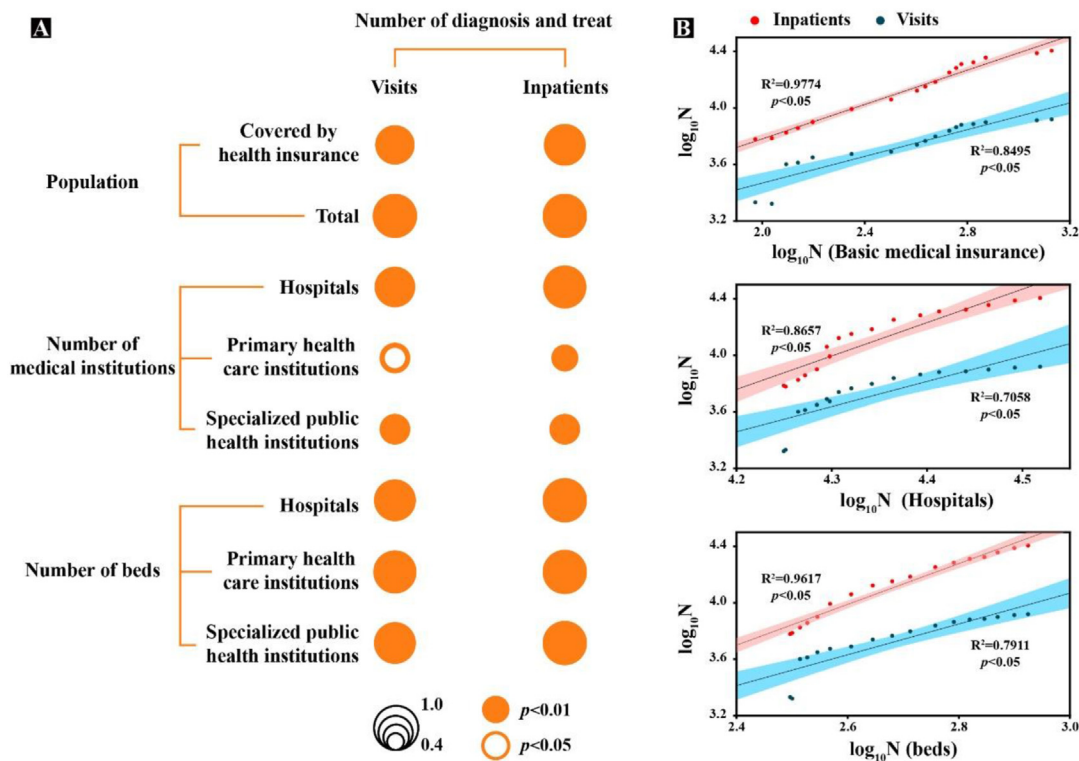


Fig. 2. The improvement of medical services has a positive effect on the number of hospitalizations visits. (A) Pearson correlation between medical services and the number of visits and inpatients. (B) Linear regression of the number of inpatients and visits with the number of basic medical insurance, hospitals and beds.

nationwide increased from more than 2000 tons at the beginning of the pandemic to a maximum of more than 3200 tons (MEE, 2020). More patients make huge medical pressure while bring a challenge for avoiding environmental pollution by medical waste.

3.2. Spatial distribution of medical waste in China

As shown in Fig. 3B, China's medical waste remarkably increased from 446 ± 9 Gg/yr in 2002 to 1536 ± 34 Gg/yr in 2018. Medical waste origin from inpatients in hospitals was the primary contributors to this change, which increased from 306 ± 6 Gg/yr in 2002 to 1165 ± 26 Gg/yr in 2018 (Fig. S3). However, regional growth showed an unbalanced feature. Nearly two-thirds of provinces had growth rates of medical waste below the national average ~240% (Fig. S4). They were concentrated in North China, Northeast and Northwest, while most of the provinces in Central South and Southwest were much higher than the national average. The largest production of medical waste was in East China and Central and South China, which reached ~450 Gg/yr and ~430 Gg/yr in 2018, respectively, both increased by more than 200% compared to 2002 (Fig. 3C, Fig. S4). The regions with the lowest production were the Northeast and the Northwest, which had similar values of ~120 Gg/yr in 2018, they increased by 165% and 359%, respectively.

China has a famous Hu line, which was proposed by a Chinese geographer Hu Huanyong in 1935 (Hu, 1935). This line connects Heihe in Heilongjiang Province and Tengchong in Yunnan Province on the map. The area on the southeast side of Hu line accounts for about 40% of China, and the population proportion exceeds 90%. Urbanization level in the southeast part of Hu line is higher than the national average, while in the northwestern part is lower. China's development for more than half a century has not changed this situation (Guo et al., 2016). It is interesting to note that the production of medical waste we estimated also showed a similar

distribution characteristic as the Hu line (Fig. 3A). There were significant positive correlations between the production of medical waste and the economy and population ($p < 0.01$) (Fig. 4). In 2002, Xizang (Tibet), among the northwest region of the Hu line, had a minimum of 760 tons/yr, and only Xinjiang reached 10,000 tons/yr. While most provinces in the southeast region exceeded 10,000 tons/yr, Guangdong reached the highest 34,000 tons/yr. By 2018, Xizang reached 2200 tons/yr, and the top province in the southeast was replaced by Sichuan, with more than 110,000 tons/yr.

However, the per capita medical waste production did not show significant regional distribution characteristics. Our results showed that there was no obvious correlation between per capita medical waste and total waste production, population, and GDP (Fig. 4), but a significant correlation with the level of household consumption ($p < 0.01$). Beijing and Shanghai have the highest per capita production, both exceeded 1.0 kg per capita, however, relatively good household consumption level also kept Xinjiang at the forefront (Fig. S5). The correlation between household consumption level and per capita production in 2002 reached 0.9 ($p < 0.01$), but this correlation decreased year by year, and fell to 0.5 in 2018 ($p < 0.01$). China just joined the World Trade Organization in 2002. At this time, residents' income was generally low, and medical payment was the critical factor in seeking medical treatment (Sun et al., 2009). Personal incomes and medical insurance have a positive effect on medical willingness, especially for rural and low-income people (Hao et al., 2010; Ohtsu et al., 2011). With the rapid development of the Chinese economy, the disposable income of residents has generally increased, the coverage of basic medical insurance has continued to expand, and the reimbursement rate of medical insurance and the types of reimbursable diseases have increased. Individual income remained no longer the determining factor in seeking medical treatment. As the times of individual medical treatment increase, therefore does the per capita medical waste.

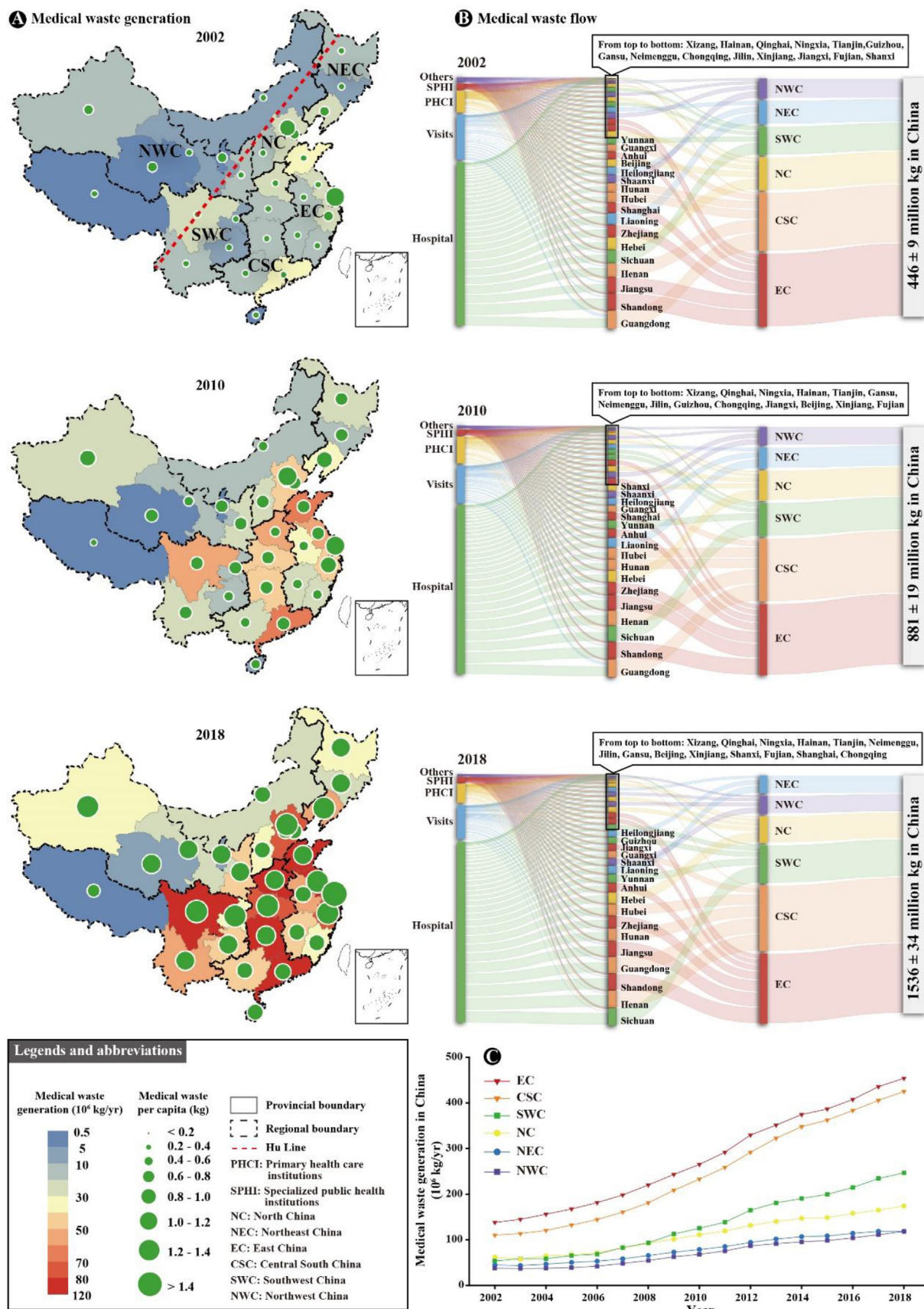


Fig. 3. Spatiotemporal distribution of medical waste in China. (A) Medical waste generation and per capita output in 2002, 2010 and 2018. (B) Characteristics of medical waste sources in different regions and provinces, the width of the line indicates the size of the flow. (C) Inter-annual changes in the production of medical waste in different regions.

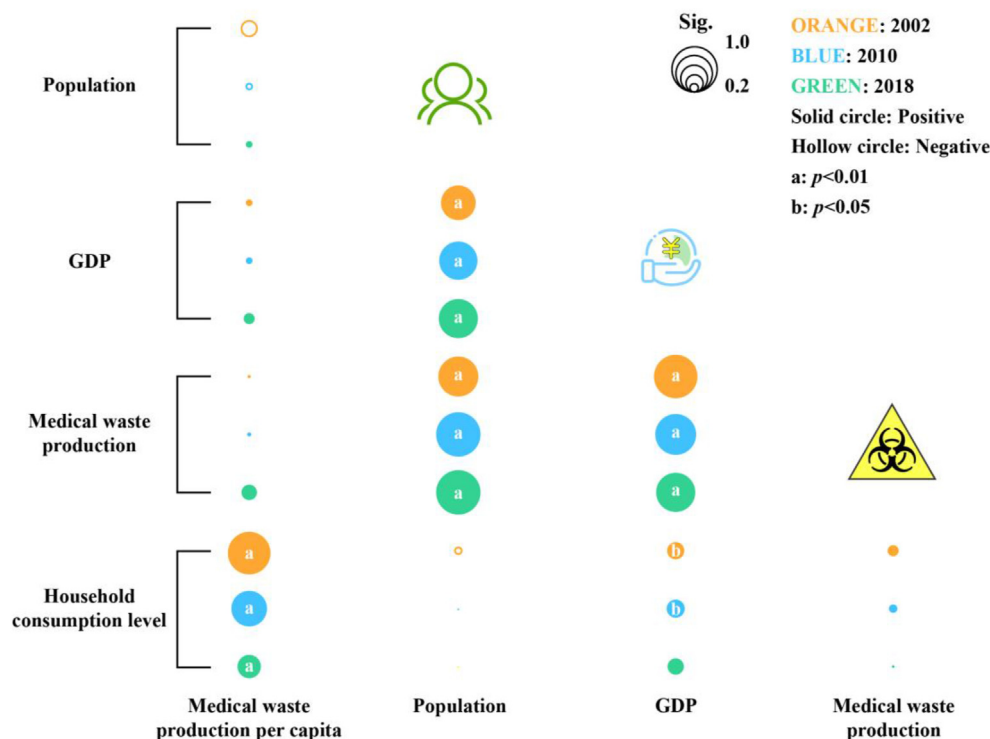


Fig. 4. Correlation between medical waste production and socio-economic factors in China in 2002, 2010, and 2018 (details in Table S2).

3.3. Environmental pollutants from growing medical waste

The production of various medical pollutants we estimated did not include the source of visits, but also showed similar spatial distribution as medical waste, that is, the production in the southeast region of the Hu line was higher and the lower in the northwest (Fig. 5A). Like medical waste, various pollutants in Sichuan were highest in China in 2018 (~28,000 tons of COD, ~10,000 tons of BOD₅, ~4800 tons of TN, ~3,300 tons of NH₃, ~370 tons of TP and ~17 kg of Hg). In 2002, all kinds of pollutants in Shandong were higher than that in Guangdong that had the highest production of medical wastes, reaching ~7500 tons of COD, ~2900 tons of BOD₅, ~1200 tons of TN, ~850 tons of NH₃, ~95 tons of TP, ~4 kg of Hg. Various pollutants in Xizang were the lowest in China all the time.

Fig. 5B shows the inter-annual variations in the total amount of various pollutants across China. Production of COD increased from 1.0×10^8 kg/yr in 2002 to 3.7×10^8 kg/yr in 2018, BOD₅ from 3.9×10^7 kg/yr to 1.4×10^8 kg/yr, TN from 1.7×10^7 kg/yr to 6.2×10^7 kg/yr, NH₄-N from 1.2×10^7 kg/yr to 4.3×10^7 kg/yr, TP from 1.3×10^6 kg/yr to 4.8×10^6 kg/yr, and Hg from 56 kg/yr to 220 kg/yr. Various pollutants have similar growth rates in the same area, but different rates in different regions (Fig. 5C). Pollutants in the northeast had the smallest increase, with an average increase of about 175%, and the highest was in the southwest with more than 420%. In all regions, the increase of the six pollutants was higher than that of medical waste, and Hg was the highest. Hg increase in the southwest region even reached 487%. The high rate of growth in the southwest was associated with the improvement of local medical conditions.

To avoid the homogeneity of variations in pollutants caused by a single pollutant producing coefficient, we tried to consider the coefficients of different medical institutions in different regions. However, the variations in the total amount of various pollutants in China were still very similar. Except Hg increased by ~290% from

2002 to 2018, the growth rates of other pollutants were similar, all about 260%. The reason may be the contribution of large hospitals plays a leading role, the number of beds in them accounts for ~70% of the total in all institutions (Fig. 1B), and the utilization rate of hospital beds was usually higher than that in other institutions, reaching more than 80%. At the same time, the proportion of hospital beds in different regions has not changed considerably since 2002 (Fig. 6A). The number of general hospital beds accounted for ~70% of the total hospital beds, and more than 50% of the total beds in all institutions. Although the number and proportion of primary health care institutions fluctuated greatly since 2002, they had a relatively weak influence on pollutant changes owing to the relatively few beds (accounted for about one-fifth of the total beds).

Cluster analysis results also confirmed the importance of general hospitals in medical institutions (Fig. 6B). When medical institutions are divided into four categories based on the number of beds, general hospitals and primary health care institutions are classified into one category respectively, that is, they have more beds than the rest. For any classification method, general hospitals are a separate category, reflecting that the number of beds is much higher than other institutions.

The discharge of medical waste without appropriate treatment will expose the public to the danger. Especially during the pandemic, reducing risks to the public and the environment is of great significance (Wang et al., 2020). However, there are relatively few studies on China's medical waste generation, and only a few areas have reported (Gai et al., 2010; Yong et al., 2009). Meanwhile, there is a lack of effective monitoring of the output of medical waste. Therefore, it is currently difficult to quantify the potential impact of medical waste on the environment, nor to identify the production pressures and environmental risks faced by different regions. Medical waste is usually treated by incineration, landfill, etc., and is not directly discharged into the water. However, due to inappropriate storage and leakage during transportation, pollutants will enter surface water and groundwater through runoff and

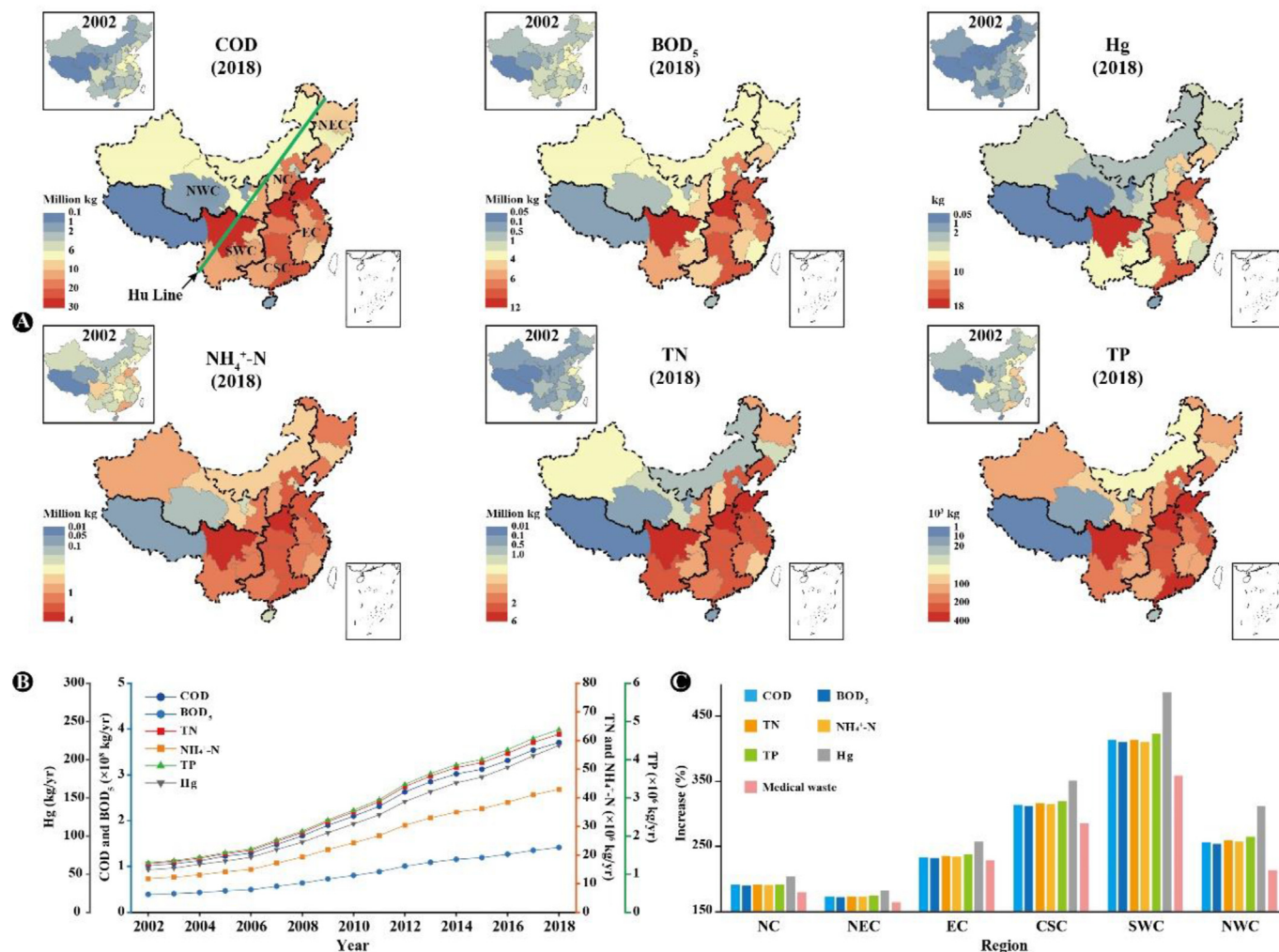


Fig. 5. Spatiotemporal distribution of pollutants from medical waste in 2002 and 2018. (A) Annual production of pollutants from medical waste by provinces, including chemical oxygen demand (COD), five-day biochemical oxygen demand (BOD_5), mercury (Hg), total nitrogen (TN), ammonia nitrogen (NH_4^+-N), and total phosphorus (TP). (B) Inter-annual change of different pollutants in China. (C) Growth percentage of pollutants in different regions from 2002 to 2018.

infiltration, which has a potential threat to the water body. Here, we tried to use the ratio of pollutants from medical waste to pollutants discharged from waste water to show the production pressure of medical waste in various regions.

Our result shows that, except for Hg, the ratios of pollutants across the country are lower than 0.06, and the ratios in Beijing and Shanghai are higher than those in other regions (Fig. 7). However, it is worth noting that Hg production from medical waste is higher than that from waste water in some regions, such as ratios of Tibet, Hebei, Shandong, Liaoning, and Hainan provinces exceed 1.0, while Beijing, Chongqing, Jiangsu, Heilongjiang provinces even more than doubled. Unlike most areas where pollutants discharged from wastewater have been declining year by year, Hg in Tibet, Hebei, Heilongjiang and Hainan provinces have increased significantly (Fig. S7). These areas are not only facing greater pressure to control Hg discharge, but may face greater environmental threats when a medical waste leakage accident occurs. Additionally, Tibet and Hainan are located on plateaus and islands respectively, which have fragile ecology, requiring special attention.

3.4. Challenges for the next decade

The results of STIRPAT model showed that except for the

number of medical institutions that was significant at 5% level, other indicators passed 1% significant test ($R^2 = 0.992$, and the F statistic is significant at 1% level). Therefore, the simulation results we obtained could reflect the relationship between medical waste growth and various factors (more details in Table S3). Each factor we selected could promote the production of medical waste as shown in Fig. 8A. Among them, the population has the strongest impact, when increase by 1%, medical waste increase by 2.47%, followed by the number of medical institutions (0.40%), and the impact of government health expenditure is the smallest, less than 0.1%. The elastic coefficient of visits (0.18%) was higher than that of hospitalizations (0.10%). The number of visits was considerably higher than hospitalizations, for instance, the number of visits reached 8.3 billion in 2018, while hospitalizations were 250 million. The greater mobility of visits may make more complex effects than inpatients. Basic medical insurance has covered most people in China, and individual income is no longer a key factor that affects the willingness of different people to seek medical care. However, medical insurance can only cover a part of the medical expenses. The huge cost of hospitalization, especially severe illness, may affect the willingness of some inpatients (Mao et al., 2013). Therefore, the elastic coefficient of the household consumption level was slightly higher than that of hospitalization. The

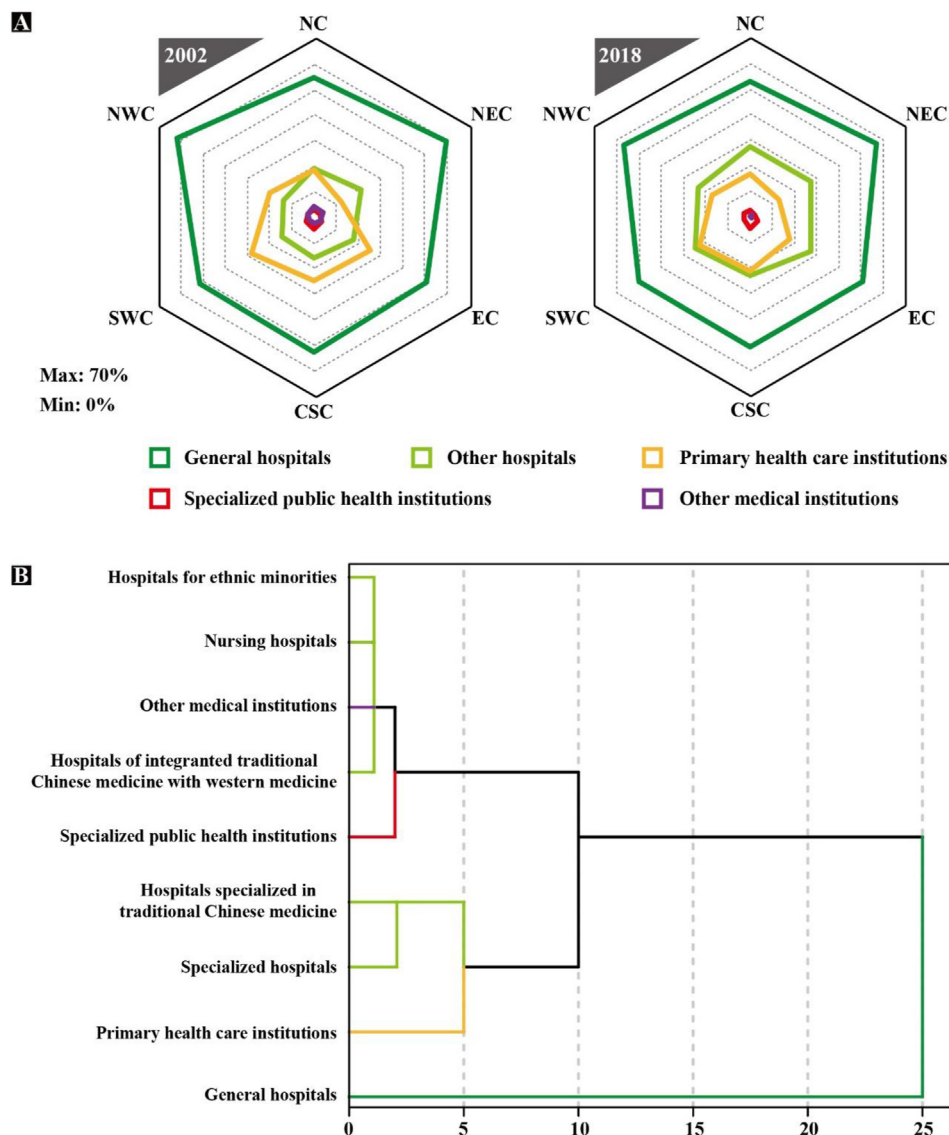


Fig. 6. Distribution of beds in different medical institutions. (A) The proportion of beds from different medical institutions in various regions, including North China (NC), Northeast China (NEC), East China (EC), Central South China (CSC), Southwest China (SWC), Northwest China (NWC). (B) Cluster analysis results of beds in different medical institutions in China (average of 2002–2018).

population is the direct cause of medical waste, and medical institutions and beds are where generating large amounts of medical waste. Thus, these three factors have the highest elastic coefficients.

Furthermore, we used the combination of ARIMA and STIRPAT models to simulate the growth of medical waste in the next ten years without the impact of the pandemic. We used the ARIMA to simulate the growth of each factor and medical waste production until 2030. Next, we brought the simulate values of each factor into the STIRPAT to obtain forecasting trends that were more constrained. We found that by 2030, medical waste production in China by STIRPAT-ARIMA would reach $\sim 2.7 \times 10^9$ kg/yr, which was 76% higher than that in 2018 (Fig. 8B).

As of mid-2020, the development of COVID-19 is still unclear, and it is temporarily difficult to assess the impact of pandemic on medical waste. However, the simulation results without pandemic constraints still show that China would face more severe pressure on medical waste disposal and environmental risk in the future. In addition, aging will deliver a more complex impact on future challenges (Pearson et al., 2012; Schneider and Guralnik, 1990). Due

to the improvement of medical conditions and the living standards, the average life expectancy in China increased from 71.4 years in 2000 to 76.3 years in 2015 (NBSC, 2001–2019a). Among discharged patients, the proportion of people over 60 years of age increased from 25.3% in 2004 to 38.8% in 2018 (NBSC, 2001–2019a). China has lifted restrictions on single children, however, the pressure of aging in China would continue in the short term in terms of the current low fertility rate. The huge population base and the growth in the proportion of the elderly increase the pressure on medical treatment, and ultimately lead to more medical waste.

3.5. Suggestions

The practical issues that we suffer to address include increasing the construction of medical waste disposal facilities, enhancing the capacity of medical waste disposal, and promoting the recycling of medical waste and saving resources, to prevent and control the pollution to the human body and the environment. SARS promoted the relevant regulations for the disposal of medical waste issued in

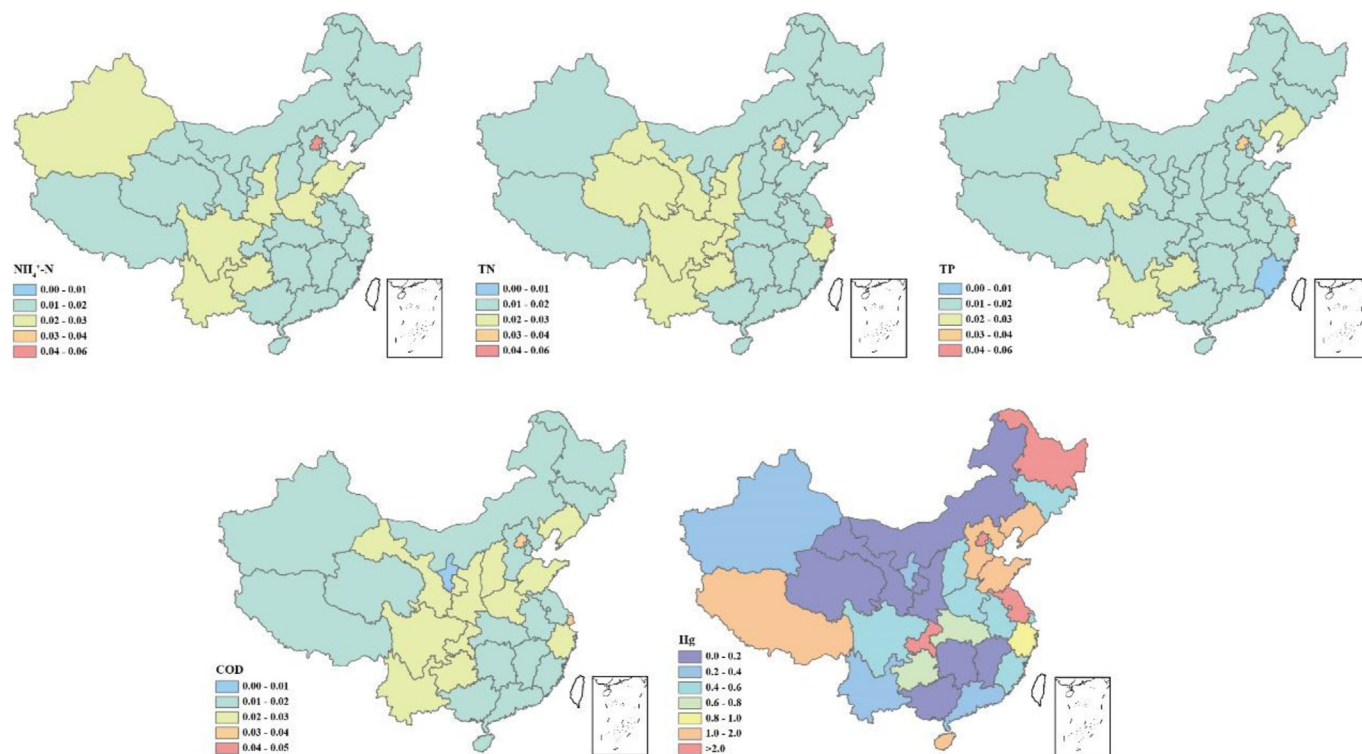


Fig. 7. Average ratio of pollutants in medical waste to pollutants in urban wastewater discharge from 2011 to 2017. The Hg data in wastewater discharge of Xizang (Tibet) are from 2012 to 2017, due to missing data in 2011.

China since 2003, and the outbreak of COVID-19 once again pushed the medical waste treatment and environmental safety to the public hot spot. In February 2020, the Chinese government issued Work Plan for Comprehensive Treatment of Waste in Medical Institutions (SCPRC, 2020), which requires all cities above the prefecture-level to build at least one centralized medical waste disposal facility by the end of 2020 and each county will build a medical waste system that consists of the collection, transfer, and disposal parts by 2022 (MEE, 2020). While proposing an ambitious large-scale construction plan of medical waste disposal facilities, the details of how to implement them are crucial. Based on this research, we submit the following suggestions:

- (i) Improve the efficiency of medical waste disposal. The population is the most important driver of medical waste, and household consumption level has a significant impact on per capita medical waste. Therefore, it is necessary to increase the number of disposal facilities in the economically developed and densely populated cities in the east, such as Beijing, Shanghai and other large cities. In the west, Xinjiang and other regions with a high per capita consumption levels also require particular attention. Moreover, in the public health emergencies, the accumulation of medical waste that cannot be processed in time would pose a threat to public and environmental health. The off-site treatment of medical waste with long-distance transportation is not advisable due to the potential risk of leakage (Tsakona et al., 2007). According to population density of different regions, equipped with a corresponding number of mobile treatment equipment would effectively speed up the processing of medical waste in special periods and achieve collaborative and mutual assistance between regions. The mobile incinerator

in Wuhan has effectively alleviated the pressure of medical waste treatment is a successful case (Singh et al., 2020).

- (ii) Increasing the ratios of beds to medical institutions. The average utilization rate of hospital beds in China has been between 85% and 90% since 2010. Hubei, where COVID-19 hit the medical system hard, at ordinary times has reached 92%–99% of hospital beds utilization (NBSC, 2001–2019a). High-load hospitalization pressure has a negative impact on responding to the public health emergency. We found the number of medical institutions had a greater impact on medical waste production than the number of beds. Increased beds can effectively reduce the amount of medical waste (Cheng et al., 2009). Therefore, when the local government considers improving the capacity of medical institutions to treat patients, it should pay more attention to the capacity of hospital beds rather than the number of medical institutions, and it would alleviate the pressure of medical waste.
- (iii) Strengthening technical research of medical waste disposal, risk assessment and biogeochemistry process. High-temperature incineration remains currently the most important method for hazardous waste, and it is the main method used for the centralized treatment of medical waste in China (Chen et al., 2013; Yang et al., 2009). However, landfilling of the fly ash and bottom slag produced by incineration without strict treatment, would cause secondary pollution to the environment (Hossain et al., 2011), especially the migration of heavy metal affected by acid rain harms the soil. At present, there have been many studies on environmental assessment methods about pollutants in soil, water and atmosphere. However, the methodologies and theoretical frameworks are still relatively lacking for environmental risk assessment, ecological damage about medical

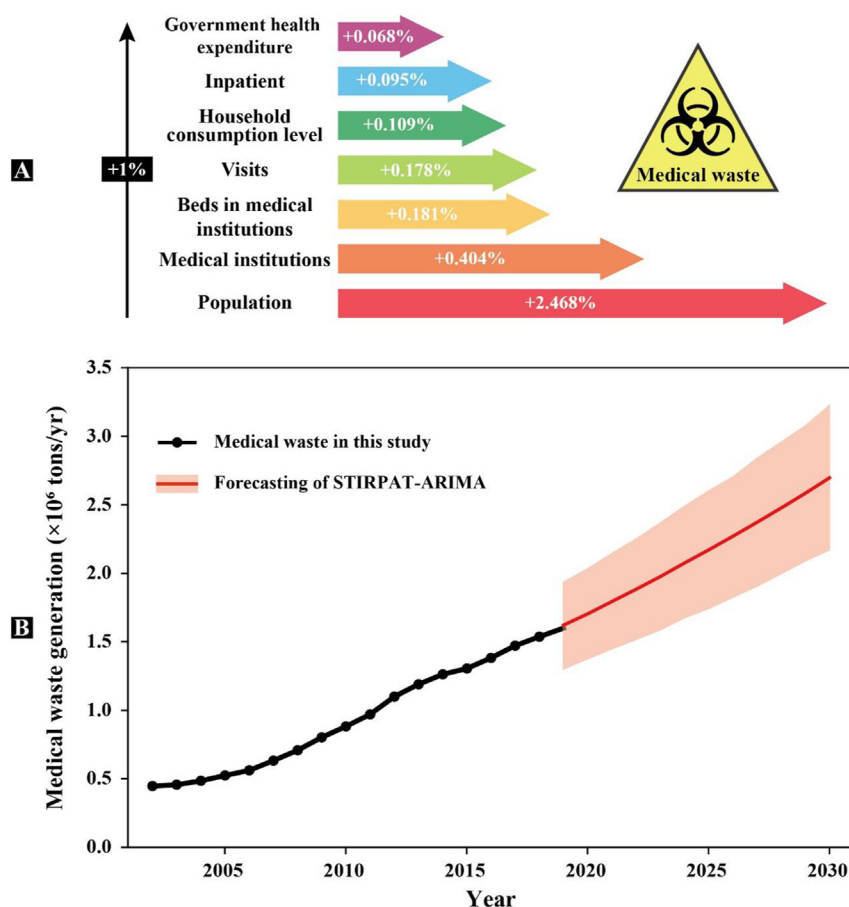


Fig. 8. Influencing factors of medical waste and future trends. (A) The elastic coefficient of socio-economic factors influenced on medical waste production in China according to STIRPAT model. (B) Forecasting future trends of medical waste production in China.

waste. It is key to strengthen the fundamental research of medical waste from the perspective of biogeochemistry. For example, quantifying pollutants during outpatient visits and sharing data will help to accurately assess the environmental impact of medical pollutants.

4. Conclusion

This study is the first to estimate the China's production of medical waste and related pollutants, and reveals their spatio-temporal heterogeneity its influencing factors. We found that the number of seeking medical treatment rapidly increase led to explosive growth in medical waste and pollutants since 2002, under the influence of health care reform and economy development, especially increase in personal income and popularization of medical insurance. Inpatients of large hospitals are the major contributors of medical waste compared with other institutions and visits, and population is the main driver of changes in medical waste. In the absence of the pandemic, the production of medical waste in 2030 would still increase by more than 50% compared with 2018 due to the huge population. The production of medical waste and pollutants in the economically developed eastern region, which has dense population, is higher than that in the west. However, the per capita medical waste is only affected by household consumption level without regional characteristic. Additionally, Hg loads from medical waste are more than that from discharged wastewater in some regions, which have great control pressure of Hg emission.

The continuous growth of medical waste in China poses huge challenges to the waste disposal system since the SARS outbreak, especially in the pandemic. In the future, to reduce the pressure of medical waste disposal and environmental risks, policymakers shall (i) increase the disposal facilities according to population density and promote mobile treatment equipment to enhance efficiency; (ii) increase the number of beds in medical institutions rather than building more hospitals; and (iii) strengthen basic research on the environmental impact of medical waste.

CRediT authorship contribution statement

Yujun Wei: Methodology, Data curation, Formal analysis, Validation, Software, Writing - original draft. **Meng Cui:** Conceptualization, Investigation, Software, Writing - review & editing, Visualization, Supervision. **Zhonghua Ye:** Resources, Validation, Writing - review & editing. **Qingjun Guo:** Funding acquisition, Methodology, Formal analysis.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Acknowledgement

The authors thank medical workers, courier deliverers, and

community service workers who stayed on the jobs during the outbreak of the Novel Coronavirus. In addition, we thank the Public Governance Institute of Qianhai Innovation Research Institute, Shenzhen, for the help in data collection and the support by the National Natural Science Foundation of China (Grant No. 41890824).

Appendix A. Supplementary data

Supplementary data to this article can be found online at <https://doi.org/10.1016/j.jclepro.2020.125246>.

References

- Abd El-Salam, M.M., 2010. Hospital waste management in El-Beheira governorate, Egypt. *J. Environ. Manag.* 91, 618–629.
- Ali, M., Kuroiwa, C., 2009. Status and challenges of hospital solid waste management: case studies from Thailand, Pakistan, and Mongolia. *J. Mater. Cycles Waste* 11, 251–257.
- Arbulu, I., Lozano, J., Rey-Maqueira, J., 2017. Waste generation flows and tourism growth: a STIRPAT model for Mallorca. *J. Ind. Ecol.* 21 (2), 272–281.
- Butt, T.E., Lockley, E., Oduyemi, K.O., 2008. Risk assessment of landfill disposal sites—State of the art. *Waste Manag.* 28, 952–964.
- Caniato, M., Tudor, T.L., Vaccari, M., 2015. International governance structures for health-care waste management: a systematic review of scientific literature. *J. Environ. Manag.* 153, 93–107.
- Chaerul, M., Tanaka, M., Shekdar, A.V., 2008. A system dynamics approach for hospital waste management. *Waste Manag.* 28, 442–449.
- Chen, J., Dong, H., Yu, H., et al., 2018. Impact of new rural cooperative medical scheme on the equity of health services in rural China. *BMC Health Serv. Res.* 18, 486.
- Chen, Y., Ding, Q., Yang, X., et al., 2013. Application countermeasures of non-incineration technologies for medical waste treatment in China. *Waste Manag. Res.* 31, 1237–1244.
- Cheng, Y.W., Sung, F.C., Yang, Y., et al., 2009. Medical waste production at hospitals and associated factors. *Waste Manag.* 29, 440–444.
- CPSC (China Pollution Source Census), 2010. First national pollution source Census. accessed. <http://cpsc.mep.gov.cn/>. (Accessed 1 August 2018).
- Dai, T., Hu, H.P., Na, X., et al., 2016. Effects of new rural cooperative medical scheme on medical service utilization and medical Expense control of inpatients: a 3-year Empirical study of Hainan province in China. *Chin. Med. J.* 129, 1280–1284.
- Ehrlich, P.R., Holdren, J.P., 1971. Impact of population growth. *Science* 191 (3977), 1212–1217.
- Gai, R., Xu, L., Li, H., Zhou, C., He, J., Yoshihisa, S., Tang, W., Chushi, K., 2010. Investigation of health care waste management in Binzhou District, China. *Waste Manag.* 30, 246–250.
- Guo, H., Wang, X., Wu, B., et al., 2016. Cognizing population density demarcative line (Hu Huanyong-line) based on space technology. *Bull. Chin. Acad. Sci.* 31, 1385–1394 (in Chinese).
- Hao, Y., Wu, Q., Zhang, Z., et al., 2010. The impact of different benefit packages of Medical Financial Assistance Scheme on health service utilization of poor population in rural China. *BMC Health Serv. Res.* 10, 170.
- Hossain, M.S., Santhanam, A., Nik Norulaini, N.A., et al., 2011. Clinical solid waste management practices and its impact on human health and environment-A review. *Waste Manag.* 31, 754–766.
- Hu, H., 1935. The distribution of population in China, with statistics and Maps. *Acta Geograph. Sin.* 2, 33–74 (in Chinese).
- Ji, X., Chen, B., 2017. Assessing the energy-saving effect of urbanization in China based on stochastic impacts by regression on population, affluence and technology (STIRPAT) model. *J. Clean. Prod.* 163, 206–209.
- Lee, C.C., Huffman, G.L., Nalesnik, R.P., 1991. Medical waste management. *Environ. Sci. Technol.* 25, 360–363.
- Li, Z.J., Gao, G.F., 2017. Infectious disease trends in China since the SARS outbreak. *Lancet Infect. Dis.* 17, 1113–1115.
- Mao, a., Hu, H., Zhou, Y., et al., 2013. The effect evaluation of catastrophic disease insurance of new rural cooperative medical scheme: based on inpatient medical records in Beijing and Hainan province (in Chinese). *Chinese Journal of Health Policy* 6, 29–34.
- Mavakala, B.K., Le Faucheur, S., Mulaji, C.K., et al., 2016. Leachates draining from controlled municipal solid waste landfill: detailed geochemical characterization and toxicity tests. *Waste Manag.* 55, 238–248.
- McKenzie, E., 1984. General exponential smoothing and the equivalent arma process. *J. Forecast.* 3, 333–344.
- MEE (Ministry of Ecology and Environment), 2019. Annual reports on the prevention and control of environmental pollution by municipal solid waste (2019) (03.20.2020). <http://www.mee.gov.cn/ywzg/gtfwyhxpj/gtfw/201912/P020191231360445518365.pdf>.
- MEE (Ministry of Ecology and Environment), 2020. Ministry of ecological environment of the People's Republic of China (03.30.2020). <http://www.mee.gov.cn/>.
- NBSC (National Bureau of Statistics of China), 2001–2019a. China Statistical Yearbook (2001–2019). China Statistics Press.
- NBSC (National Bureau of Statistics of China), 2001–2019b. China Rural Statistical Yearbook (2001–2019). China Statistics Press.
- NHCPRC (National Health Commission of the People's Republic of China), 2001–2019. China Health Statistical Yearbook (2001–2019). Peking Union Medical College Press.
- Ohtsu, T., Toda, R., Shiraishi, T., et al., 2011. Living conditions, ability to seek medical treatment, and awareness of health conditions and healthcare options among homeless persons in Tokyo, Japan. *Acta Med. Okayama* 65, 387–393.
- Pearson, W.S., Bhat-Schelbert, K., Probst, J.C., 2012. Multiple chronic conditions and the aging of America: challenge for primary care physicians. *J. Prim Care Community Health* 3, 51–56.
- Schneider, E.L., Guralnik, J.M., 1990. The aging of America. Impact on health care costs. *Jama* 263, 2335–2340.
- SCPRC (The State Council, the People's Republic of China), 2020. Work plan for comprehensive treatment of waste in medical institutions (03.20.2020). http://www.gov.cn/zhengce/zhengceku/2020-02/27/content_5483928.htm.
- Shi, A., 2003. The impact of population pressure on global carbon dioxide emissions, 1975–1996: evidence from pooled cross-country data. *Ecol. Econ.* 44 (1), 29–42.
- Silva, A., Prata, J., Walker, T., Campos, D., Duarte, A., Soares, A., Barcelò, D., Rocha-Santos, T., 2020. Rethinking and optimising plastic waste management under COVID-19 pandemic: policy solutions based on redesign and reduction of single-use plastics and personal protective equipment. *Sci. Total Environ.* 742, 140565.
- Singh, N., Tang, Y., Zhang, Z., Zheng, C., 2020. COVID-19 waste management: effective and successful measures in Wuhan, China. *Resour. Conserv. Recycl.* 163, 105071.
- Sun, N., Wu, S., Hou, G., 2007. Implementation status, Barriers and suggestions on national construction planning of medical waste disposal facilities. *Research of Environmental Sciences* 20, 158–163 (in Chinese).
- Sun, N., Zhang, Z., Zhang, Z., et al., 2015. Practice and consideration of demonstration of comprehensive management and collaborative disposal of medical wastes in Gansu province. *Environ. Prot. Sci.* 41, 153–158 (in Chinese).
- Sun, X., Jackson, S., Carmichael, G., et al., 2009. Catastrophic medical payment and financial protection in rural China: evidence from the new cooperative medical scheme in Shandong province. *Health Econ.* 18, 103–119.
- Taghipour, H., Mosaferi, M., 2009. Characterization of medical waste from hospitals in Tabriz, Iran. *Sci. Total Environ.* 407, 1527–1535.
- Tsakona, M., Anagnostopoulou, E., Gidarakos, E., 2007. Hospital waste management and toxicity evaluation: a case study. *Waste Manag.* 27, 912–920.
- Wang, J., Shen, J., Ye, D., Yan, X., Zhang, Y., Yang, W., Li, X., Wang, J., Zhang, L., Pan, L., 2020. Disinfection technology of hospital wastes and wastewater: suggestions for disinfection strategy during coronavirus Disease 2019 (COVID-19) pandemic in China. *Environ. Pollut.* 262, 114665.
- Wang, Q., Wu, S., Zhang, Y., et al., 2013. Considerations on medical waste sound disposal and management strategies in China. *Chinese Journal of Environmental Management* 5, 49–53 (in Chinese).
- Windfeld, E.S., Brooks, M.S., 2015. Medical waste management-A review. *J. Environ. Manag.* 163, 98–108.
- Yang, B., 2018. Status and economic countermeasures of medical waste treatment in Shanghai. *Environmental Science and Management* 43, 62–66 (in Chinese).
- Yang, C., Peijun, L., Lupi, C., et al., 2009. Sustainable management measures for healthcare waste in China. *Waste Manag.* 29, 1996–2004.
- Yang, L., Xia, H., Zhang, X., Yuan, S., 2018. What matters for carbon emissions in regional sectors? A China study of extended STIRPAT model. *J. Clean. Prod.* 180, 595–602.
- Yao, L.N., Chen, E.F., Chen, Z.P., et al., 2013. From SARS to H7N9: the mechanism of responding to emerging communicable diseases has made great progress in China. *Bioscience Trends* 7, 290–293.
- Yong, Z., Gang, X., Guanxing, W., et al., 2009. Medical waste management in China: a case study of Nanjing. *Waste Manag.* 29, 1376–1382.
- York, R., Rosa, E.A., Dietz, T., 2003a. A rift in modernity? Assessing the anthropogenic sources of global climate change with the STIRPAT model. *Int. J. Sociol. Soc. Pol.* 23 (10), 31–51.
- York, R., Rosa, E.A., Dietz, T., 2003b. STIRPAT, IPAT and ImPACT: analytic tools for unpacking the driving forces of environmental impacts. *Ecol. Econ.* 46 (3), 351–365.
- You, S., Sonne, C., Ok, Y., 2020. COVID-19's unsustainable waste management. *Science* 368 (6498), 1438–1438.
- Zhang, H.J., Zhang, Y.H., Wang, Y., et al., 2013. Investigation of medical waste management in Gansu Province, China. *Waste Manag. Res.* 31, 655–659.
- Zhao, C., Chen, B., Hayat, T., Alsaedi, A., Ahmad, B., 2014. Driving force analysis of water footprint change based on extended STIRPAT model: evidence from the Chinese agricultural sector. *Ecol. Indic.* 47, 43–49.
- Zhu, J., Ren, Z., Li, Y., et al., 2016. Study on economic policy for medical waste treatment and disposal in Hubei. *Environment and Development* 28, 15–19 (in Chinese).